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On the exponential series of formal groups

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§1. Introduction

Let p be an odd prime. In the prime cyclotomic field $\mathbb{Q}_p(\zeta_p)$ generated by a primitive p-th root ζ_p of unity over the p-adic rationals $\mathbb{Q}_p$, there are explicit formulas of Takagi for the reciprocity law.

Let $\mathfrak{p}_0 = (1-\zeta_p)$ denote the prime ideal in $\mathbb{Q}_p(\zeta_p)$, and select a prime element $\tilde{\omega}$ such that

$$\tilde{\omega} = \sqrt[p-1]{-p}\ , \quad \tilde{\omega} \equiv \zeta_p - 1 \pmod{\mathfrak{p}_0^2}\ .$$

Take Takagi basis κ_i $(1 \leqq i \leqq p)$ as basis for the multiplicative group of the principal units U_1 modulo $\mathfrak{p}_0^{p+1}$ in $\mathbb{Q}_p(\zeta_p)$. Then the following formulas for the p-th norm residue symbol $(\ ,\ )$ hold.

$$(\kappa_i, \kappa_j) = 1 \quad \text{for} \quad i+j \not\equiv 1 \pmod{p-1}\ ,$$

$$(\kappa_i, \kappa_j) = \zeta_p^{-i} \quad \text{for} \quad i+j \equiv 1 \pmod{p-1}\ ,$$

$$(\tilde{\omega}\ , \kappa_i) = 1 \quad \text{for} \quad i = 1,2,\cdots, p-1\ ,$$

$$(\tilde{\omega}\ , \kappa_p) = \zeta_p\ .$$

For any principal unit $\nu \in U_1$ we have the congruence with some integers $t_i(\nu) \in \mathbb{Z}$, called the Takagi exponents,

$$\nu \equiv \kappa_1^{t_1(\nu)} \kappa_2^{t_2(\nu)} \cdots\cdots \kappa_p^{t_p(\nu)} \pmod{\mathfrak{P}_0^{p+1}} .$$

Then it holds that for any $\nu, \mu \in U_1$

$$(\nu,\mu) = \zeta_p^{-\sum_{i=1}^{p-1} i t_i(\nu) t_{p-i}(\mu)} ,$$

$$(\tilde{\omega},\nu) = \zeta_p^{t_p(\nu)} .$$

These are called Takagi's formulas.

Now, the power series on indeterminate X

$$E(X) = e^{L(X)} = \prod_{(m,p)=1} (1-X^m)^{-\frac{\mu(m)}{m}}$$

with $L(X) = \sum_{\ell=0}^{\infty} \frac{1}{p^\ell} X^{p^\ell}$ is known as the Artin-Hasse exponential series, and $E(X) \in \mathbb{Z}_p[[X]]$ plays the central role in the proof for the complementary laws of reiprocity in the cyclotomic case [1]. Then we have the congruences

$$\kappa_i \equiv E((-1)^{i-1}\tilde{\omega}^i) \pmod{\mathfrak{P}_0^{p+1}} \quad (1 \leqq i \leqq p) .$$

For the details we refer to [6].

§2. Exponential series of the Lubin-Tate groups

Let k be a finite extension over $\mathbb{Q}_p$, and $\mathfrak{o}$ the integer ring, $\mathfrak{p}$ the prime ideal, π a fixed prime element in k respectively. Let $q = p^c$ denote the number of the elements of the residue class field of k, namely, $\mathfrak{o}/\mathfrak{p} = GF(q)$.

Let $f(X) \in \mathfrak{o}[[X]]$ be a Frobenius power series belonging to the prime element π, namely

$$f(X) \equiv \pi X \pmod{\deg 2}, \quad f(X) \equiv X^q \pmod{\pi}$$

hold. Then there is a unique Lubin-Tate formal group $F = F_f$ attached to the series f, especially $f(X) = [\pi]_F(X)$ is an endomorphism of F.

Let $\Lambda_{f,m}$ denote the group of π^m division points in the algebraic closure k_s of k, and $L_{\pi,m} = k(\Lambda_{f,m})$ the field of π^m division points over k. Then we denote the integer ring, the prime ideal in $L_{\pi,m}$ by $\mathfrak{o}_{m-1}$, $\mathfrak{p}_{m-1}$ respectively.

Now, for any $\alpha \in F(\mathfrak{p}_n)$, $\beta \in L^{\times}_{\pi,n+1}$ take an element $\gamma \in k_s$ such that $[\pi^{n+1}]_F(\gamma) = \alpha$, and define the norm residue symbol $(\alpha,\beta)^F_n$ due to Wiles [5], [7] as follows :

$$(\alpha,\ \beta)^F_n = \sigma_\beta \gamma \underset{F}{-} \gamma \in \Lambda_{f,n+1}, \quad \sigma_\beta = (\beta,\ L^{ab}_{\pi,n+1}/L_{\pi,n+1}) ,$$

where $L^{ab}_{\pi,n+1}$ means the maximal abelian extension of $L_{\pi,n+1}$ and $\sigma_\beta \in G(L^{ab}_{\pi,n+1}/L_{\pi,n+1})$ denotes the Artin map in local class field theory.

There is the isomorphism $\lambda_F : F \cong G_a$ from the group F to the additive formal group G_a over k satisfying $\lambda_F'(0) = 1$. This power series $\lambda_F(X) \in k[[X]]$ is called the logarithm of F and is explicitly given by a formula

$$\lambda_F(X) = \lim_{n\to\infty} \frac{1}{\pi^n}[\pi^n]_F(X) .$$

The inverse power series $e_F : G_a \cong F$ with $e_F'(0) = 1$ is called the exponential series of F.

Now, we define an exponential series $E_F(X)$ as follows :

$$E_F(X) = e_F(L(X)) \quad \text{with} \quad L(X) = \sum_{\ell=0}^{\infty} \frac{1}{\pi^\ell} X^{q^\ell} .$$

Then we see $E_F(X) \in k[[X]]$, but more precisely $E_F(X) \in X\mathfrak{o}[[X]]$. This fact depends on the generalization of the Dieudonné-Dwork lemma.

Lemma 1. It is necessary and sufficient for a power series $P(X) \in Xk[[X]]$ to belong to $X\mathfrak{o}[[X]]$ that $P(X^q)\overline{F}[\pi]_F(P(X))$ has all the coefficients divisible by π, namely

$$P(X^q)\overline{F}[\pi]_F(P(X)) \in X\pi\mathfrak{o}[[X]].$$

The Dieudonné-Dwork lemma is a special case of Lemma 1 for the multiplicative group G_m and $\mathfrak{o} = \mathbb{Z}_p$.

By the definition of $E_F(X)$ we have directly

$$E_F(X^q)\overline{F}[\pi]_F(E_F(X)) = e_F(-\pi X) ,$$

and we know $e_F(\pi X) \in X\pi\mathfrak{o}[[X]]$. Consequently we conclude from Lemma 1 that

$$E_F(X) \in X\mathfrak{o}[[X]] .$$

§3. Complementary laws

We consider the basic formal group ξ attached to $f(X) = \pi X + X^q$.

For each $n \geqq 0$ we take a prime element $u_n \in \Lambda_{f,n+1}$ in $L_{\pi,n+1}$ such as $[\pi]_\xi(u_n) = u_{n-1}$, $[\pi]_\xi(u_0) = 0$.

It holds from the Iwasawa-Wiles formula [2], [5], [7] that for any $i \geqq 1$

$$(E_\xi(u_n^i),\ u_n)_n^\xi = [\frac{1}{\pi^{n+1}}\ T_n(\frac{\lambda_\xi(E_\xi(u_n^i))}{\lambda_\xi'(u_n)u_n})]_\xi(u_n),$$

where T_n denotes the trace with respect to $L_{\pi,n+1}/k$.
By the way we have $\lambda_\xi(E_\xi(u_n^i)) = L(u_n^i) \in L_{\pi,n+1}$, because we have in general $\lambda_F(X) = \sum_{m=1}^{\infty} \frac{c_m}{m} X^m$ with $c_m \in \mathfrak{o}$. Thus we have

$$(E_\xi(u_n^i),\ u_n)_n^\xi = [\frac{1}{\pi^{n+1}}\ T_n(\frac{L(u_n^i)}{\lambda_\xi'(u_n)u_n})]_\xi(u_n) .$$

Lemma 2. Assume $\ell \geqq 2n + 2$. Then we have

$$\frac{1}{\pi^\ell}\ T_n(\frac{u_n^{iq^\ell-1}}{\lambda_\xi'(u_n)}) \equiv 0 \pmod{\pi^{2(n+1)}} .$$

This can be obtained by virtue of the different $\mathfrak{d}_n$ equal to $\mathfrak{p}_n^{q^n((n+1)(q-1)-1)} \sim \pi^{n+1}u_0^{-1}\mathfrak{o}_n$.

Lemma 3. We have

$$T_n\left(\frac{u_n^r}{\lambda'_\xi(u_n)}\right) = \begin{cases} 0 & \text{for } 0 \leqq r \leqq q^n-2 , \\ -\pi^n & \text{for } r = q^n-1. \end{cases}$$

Especially

$$\frac{1}{\pi^\ell} T_n\left(\frac{u_n^{iq^\ell-1}}{\lambda'_\xi(u_n)}\right) = 0 \quad \text{for } iq^\ell < q^n ,$$

$$\frac{1}{\pi^n} T_n\left(\frac{u_n^{q^n-1}}{\lambda'_\xi(u_n)}\right) = -1.$$

These formulas come out from Euler's identity, Lagrange's interpolation formula for polynomials. The next lemma follows similarly from the same and noticing the minimal basis of $L_{\pi,n+1}/L_{\pi,n}$ to be $1, u_n, \cdots, u_n^{q-1}$. $T_{n,n-1}$ denotes the trace with respect to $L_{\pi,n+1}/L_{\pi,n}$.

Lemma 4. Assume $n \geqq 1$. Then we have

$$T_{n,n-1}\left(\frac{u_n^r}{\lambda'_\xi(u_n)}\right) = \begin{cases} 0 & \text{for } 0 \leqq r \leqq q-2 , \\ \dfrac{\pi}{\lambda'_\xi(u_{n-1})} & \text{for } r = q-1 , \end{cases}$$

$$T_{n,n-1}\left(\frac{u_n^r}{\lambda'_\xi(u_n)}\right) = \frac{\pi}{\lambda'_\xi(u_{n-1})} \sum_{\substack{s_0, r_1 \geqq 0 \\ (q-1)(s_0+1)+r_1=r}} (-1)^{s_0-r_1} \binom{s_0}{r_1} u_{n-1}^{r_1} \pi^{s_0-r_1} \quad \text{for } r \geqq q.$$

Now, by a repeated use of Lemma 4 we see

$$T_{n,0}\left(\frac{u_n^r}{\lambda'_\xi(u_n)}\right) = \sum(-1)^{s_0+\cdots+s_{n-1}-r_1-\cdots-r_n}\binom{s_0}{r_1}\binom{s_1}{r_2}\cdots\binom{s_{n-1}}{r_n}\pi^{n+(s_0+\cdots+s_{n-1})-(r_1+\cdots+r_n)}\frac{u_0^{r_n}}{\lambda'_\xi(u_0)}.$$

where the summation is taken over the integers s_i, $r_i \geqq 0$ satisfying $(q-1)(s_i+1) + r_{i+1} = r_i$ $(0 \leqq i \leqq n-1)$, $r_0 = r$.

Therefore, after noticing that $T_0(u_0^{r_n}) = 0$ for $r_n \not\equiv 0 \pmod{q-1}$ and $r_n \equiv r \pmod{q-1}$, we have

$$(E_\xi(u_n^i),\ u_n)_n^\xi = 0 \quad \text{for} \quad i \not\equiv 1 \pmod{q-1}\ .$$

In the sequel we compute $(E_\xi(u_n^i),\ u_n)_n^\xi$ for the cases $i \equiv 1 \pmod{q-1}$.

First, from Lemma 4 for $iq^\ell \geqq q^n$

$$(*)_\ell \qquad \frac{1}{\pi^\ell} T_n\left(\frac{u_n^{iq^\ell-1}}{\lambda'(u_n)}\right)$$

$$= \sum_{j_1,\cdots,j_n}(-1)^{j_0-n-1}\binom{j_0-1-j_1}{j_1(q-1)}\binom{j_1-1-j_2}{j_2(q-1)}\cdots\binom{j_{n-1}-1-j_n}{j_n(q-1)}\pi^{j_0-(q-1)(j_1+\cdots+j_n)-\ell}\ ,$$

where $j_0 = \frac{iq^\ell-1}{q-1}$ and j_m runs over the integers satisfying $\frac{q^{n-m}-1}{q-1} \leqq j_m \leqq \frac{1}{q}(j_{m-1}-1)$.

Here we can find easily the minimum of all the exponents of π, when ℓ and $j_1,\cdots,j_n$ run over the possible ranges under the assumption $1 \leqq i \leqq q^{n+1}-1$, $i \equiv 1 \pmod{q-1}$. The minimum exponent becomes $t + s_q(\frac{i-q^t}{q-1})$, where t means the non-negative integer such that $q^t \leqq i < q^{t+1}$ and $s_q(x)$ denotes the sum of the coefficients of the canonical q-expansion of x.

Consequently, under the condition $q > 2n + 2$ we have a congruence

$$\frac{1}{\pi^{n+1}} T_n\left(\frac{L(u_n^i)}{\lambda'_\xi(u_n)u_n}\right) \equiv \frac{1}{\pi^{n+1}} A_0^{(i)} \pi^{t+s_q(\frac{i-q^t}{q-1})} \pmod{\pi^{n+1}},$$

where $A_0^{(i)} \in \mathbb{Z}$ is the sum of all coefficients of terms with the exponent $t + s_q(\frac{i-q^t}{q-1})$ of π in the formulas $(*)_\ell$, $n-t \leqq \ell \leqq n$.

After a simple observation we see that there are two terms with coefficients not zero to be considered, namely in the cases $\ell = n-t$, $n-t+1$. Furthermore, these coefficients cancel out. Thus we obtain

$$(E_\xi(u_n^i),\ u_n)_n^\xi = 0 \quad \text{for} \quad 1 \leqq i \leqq q^{n+1} - 1.$$

Because there is the isomorphism $\phi : \xi \cong F$, $\phi'(0) = 1$ and $(\alpha, \beta)_n^F = \phi(\phi^{-1}(\alpha, \beta)_n^\xi)$ holds, we obtain, by denoting $v_n = \phi(u_n)$, the following

Theorem 1. Under the assumption $q > 2n + 2$ we have

$$(E_F(u_n^i),\ u_n)_n^F = 0 \quad \text{for} \quad 1 \leqq i \leqq q^{n+1} - 1,$$

$$(E_F(u_n^{q^{n+1}}),\ u_n)_n^F = v_n .$$

The second formula follows from the fact that $E_\xi(u_n^q) = [\pi]_\xi(E_\xi(u_n)) \underset{\xi}{-} e_\xi(\pi u_n)$, and repeatedly $E_\xi(u_n^{q^{n+1}}) = [\pi^{n+1}]_\xi(E_\xi(u_n)) \underset{\xi}{-} e_\xi(\pi^{n+1}u_n + \pi^n u_n^q + \cdots + \pi u_n^{q^n})$, and from Lemma 3, namely $(E_\xi(u_n^{q^{n+1}}), u_n)_n^\xi = u_n$.

§4. Explicit formulas in prime division fields

In this section we give a generalization of Takagi's formulas stated in Introduction.

First, the formula of de Shalit reads as follows [2] :

For $\alpha \in F(\mathfrak{p}_n)$, $\beta \in L_{\pi,n+1}^\times$ take a power series $h \in X\mathcal{O}[[X]]$ such that $\alpha = h(v_n)$ and the Coleman power series $g(X) \in X\mathcal{O}[[X]]$ with $\beta = g(v_n)$. Then it holds that

$$(\alpha, \beta)_n^F$$
$$= [\frac{1}{\pi^{n+1}}\{\sum_{\nu \in \Lambda_{f,n+1}} (\lambda_F \circ h - \frac{\lambda_F \circ h \circ [\pi]_F}{\pi}) \delta g(v) + \frac{dh}{dX}(0)(1 - \frac{Ng}{g})(0)\}]_F(v_n) ,$$

where Ng denotes Coleman's norm operator of g and δg means the logarithmic derivative of g, namely $(\delta g)(X) = \frac{1}{\lambda_F'(X)} \frac{1}{g(X)} \frac{d}{dX} g(X)$.

By making use of de Shalit formula we obtain the following

Lemma 5. For $i \geqq q$ or $j \geqq q$ or $i \not\equiv 1 \pmod{(j, q-1)}$ we have

$$\frac{1}{\pi} T_0\left(\frac{L(u_0^i) j u_0^{j-1}}{\lambda_\xi'(u_0)(1-u_0^j)}\right) \equiv 0 \pmod{\pi} .$$

For $q = i + mj$, $1 \leqq m \leqq q - 1$, $1 \leqq i, j$

$$\frac{1}{\pi} T_0\left(\frac{L(u_0^i) j u_0^{j-1}}{\lambda_\xi'(u_0)(1-u_0^j)}\right) \equiv \begin{cases} 0 & (\mathrm{mod}\ \pi) \quad (i = 1), \\ j & (\mathrm{mod}\ \pi) \quad (i \geqq 2). \end{cases}$$

Thus we have under the condition $q = i + mj$

$$(E_\xi(u_0^i),\ 1-u_0^j)_0^\xi = [-j]_\xi(u_0) \quad \text{for} \quad i \geqq 1 .$$

From this lemma we obtain

$$(E_\xi(u_0^i),\ E(u_0^j))_0^\xi = [j]_\xi(u_0) \quad \text{for} \quad q = i + p^a j ,$$

$$(E_\xi(u_0^i),\ E(u_0^j))_0^\xi = 0 \quad \text{otherwise.}$$

Herein $E(X)$ is the ordinary Artin-Hasse exponential series in Introduction.

Finally, for any Lubin-Tate group F isomorphic to ξ over $\mathfrak{o}$ belonging to the prime π we obtain the following

Theorem 2. We have

$$(E_F(u_0^i),\ E(u_0^j))_0^F = [j]_F(v_0) \quad \text{if} \quad q = i + p^a j,\ p^a | q ,$$

$$(E_F(u_0^i),\ E(u_0^j))_0^F = 0 \quad \text{otherwise} ,$$

$$(E_F(u_0^i),\ u_0)_0^F = 0 \quad \text{if} \quad 1 \leqq i \leqq q - 1 ,$$

$$(E_F(u_0^q),\ u_0)_0^F = v_0 .$$

In particular, in the case where $k = \mathbb{Q}_p$, $q = p$, $F = G_m$, $\pi = p$ and necessarily $v_0 = \zeta_p^{-1} - 1$, $u_0 = -\tilde{\omega}$, the formulas in Theorem 2 coincide just with Takagi's formulas quoted in Introduction.

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